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PSR J0045–7319: A dual-line binary radio pulsar

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Binary radio pulsars are superb tools for mapping binary orbits, because of the precision of the pulse timing method.[1] To date, all orbital parameters for binary pulsars have been derived from observations of the pulsar alone. The only known pulsar in the Small Magellanic Cloud (SMC), PSR J0045 - 7319, was discovered in a systematic search for radio pulsars in the Magellanic Clouds.[2] It was recently shown[3] to be in a 51-day binary orbit of Eccentricity 0.8. The pulsar's mass function of 2.17 $M_\odot$, implies a minimum companion mass of 4.0 $M_\odot$ for a 1.4 $M_\odot$ pulsar. Since the maximum mass for a neutron star is 3.0 $M_\odot$,[4,5] the companion must be either a black hole or a massive non-degenerate star. The B1 V star identified at the position of the pulsar is a strong candidate for the companion.[3] Here we describe the first observations of the radial velocity of a binary companion to a radio pulsar. Our results unambiguously prove that the companion to the pulsar PSR J0045- 7319 is the B1V star identified by Kaspi *et al.* (1994). The mass ratio of the system is 6.3 ± 1.2, which, for a neutron star mass of 1.4 $M_\odot$, is consistent with the mass expected for a B1 V star.

For a B1V star companion, several observable effects are expected, since the pulsar approaches to within six stellar radii from the star at periastron. At radio wavelengths, effects that would vary with orbital phase include dispersion, scattering and absorption of the pulsed emission. However, the only orbital-phase-dependent variations observed are systematic frequency independent timing residuals with respect to a Keplerian orbit.[6] Optically, the star should show radial velocity variations with an amplitude of approximately 30 km s^{-1}. It has also been suggested that the companion may exhibit resonant flux variations excited by the eccentric orbit.[7] In contrast, if the true companion is a black hole[8] and the B1V star is not associated, none of the above effects should be observed.

In order to search for these radial velocity variations, spectra having a resolution of 0.55Å per pixel, with 500Å centred on 3900Å were obtained at nine epochs using the Australian National University's 2.3 *m* telescope at Siding Spring, NSW Australia. The oxygen doublet at 3728Å from a surrounding 1111 region was used as a radial velocity standard. Helium argon arcs were used to determine the dispersion. Radial velocities were obtained by Fourier cross correlation of the spectra.

With the binary period, longitude and epoch of periastron and eccentricity determined from radio observations,[6] the systemic radial velocity and amplitude of the companion's radial velocity variation were determined using a least squares fit to the observed velocities. The fit to the radial velocity Curve is shown in Figure 1 along with the residuals and the pulsar's radial velocity curve. This fit gives a mass ratio of 6.3 ± 1.2. For a neutron star mass[9] of 1.4 $M_\odot$, this gives a companion mass of 8.8 ± 1.8 $M_\odot$ and an inclination angle for the binary 01 44 ± 5 degrees. The derived mass is marginally lower than the typical mass of a B1V star, $\sim$11$M_\odot$.[10] A good test of the stability of such a fit is to remove the point that appears most C1'11('iii] and check how much the parameters change by. Applying; this test by removing the point just after orbital phase zero, only changes the fitted parameters by 12%.

A key implication is that the wind of the companion is tenuous compared with those of typical Galactic B stars, as was suggested by Kaspi *et al.* (1994). Selection may play a role here, as higher stellar wind densities might have rendered the pulsar invisible as in the case of PSR B1259 63 near periastron.[11] The derived rotational velocity for the companion is 280 ± 20 km s^{-1}. A high rotational velocity for the companion is expected, since these rotational velocities arc common amongst main sequence B1 stars and evolutionary scenarios[12] for this type of system involve mass transfer from the pulsar progenitor to the companion, which serve to spin it up.

We find the radial velocity of the companion to be 10 ± 7 km s-1 relative to the surrounding nebula NGC 248 (N13A -I N13B). [13] The heliocentric radial velocity of 127 ± 7 km s^{-1} for NGC 248 compares well with the previously measured value[14] of 131 ± 2.5 km S-]. '1'11(' heliocentric velocity of the binary system of I 17 ± 7 km s^{-1} is consistent with the uncertainties with the 167 ± 40 km s^{-1}, estimated from low dispersion spectra.'' The heliocentric velocities of both the PSR J0045 7319 binary and NGC '248 arc somewhat less than the mean heliocentric radial velocity for the SMC[15] of 160 km s-' . However, when one considers radial velocities of the four components of the SMC,[15] -45, 28, 9 and 30 km s-' (relative to the mean), the difference is not surprising.

Heliocentric radial velocities for M stars[16] in the same region as PSR J0045-7319 are similar to that of PSR J0045-7319.

The results outlined here provide unambiguous evidence that the B1V star identified by Kaspi *et al.*[3] is the companion to PSR J0045-7319, and rule out a black hole companion as proposed by Lipunov *et al.* (1994). The fact that no known radio pulsar has a black hole companion means that we have no definitive proof that such systems exist, despite the existence of objects such as Cygnus X-3[17] which might be expected to form a black hole-neutron star binary in the future. This might be because binaries containing black holes are particularly susceptible to coalescence during the final common-envelope phase of their evolution. However the expected number of observable pulsar black hole binaries given the statistics of the known pulsar population is only of the order of one.[18,19]

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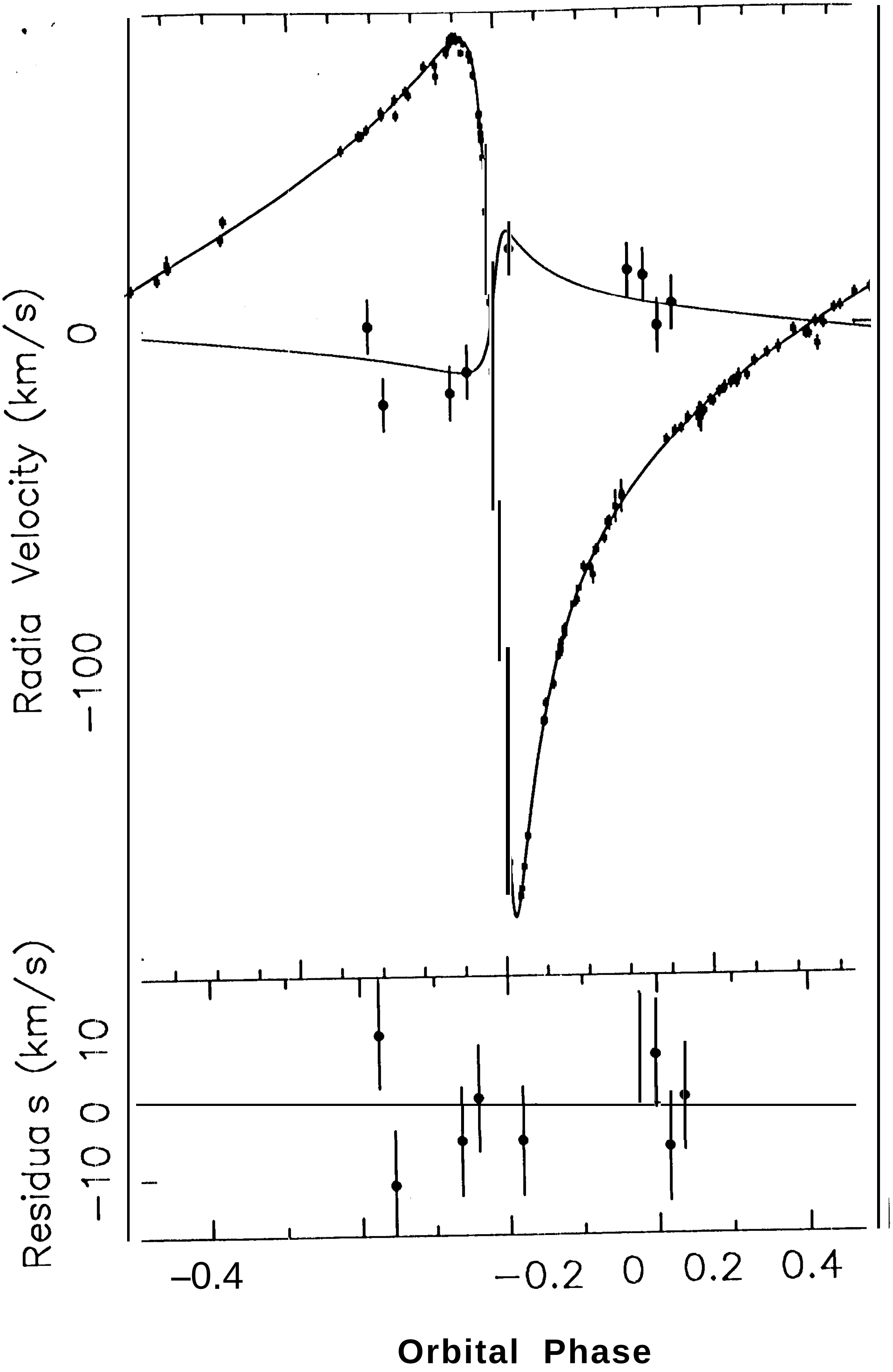
Figure 1. Top: Radial velocity data and fitted curves for the radio observations[6] (large amplitude curve) and for the companion, from optical observations (small amplitude curve). Bottom: Residuals of the two parameter fit to the optical radial velocity variations of the companion. In both panels the error bars shown are ± one standard deviation.



Radia Velocity (km/s)
0
−100
Residua s (km/s)
10
0
−10
−0.4
−0.2
0
0.2
0.4
Orbital Phase